

Research article

Periodontal disease in sheep and cattle: Understanding dental health in past animal populations

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ARTICLE INFO

Keywords:

Calculus

Age

Alveolar recession

Zooarchaeology

Palaeopathology

ABSTRACT

Objective: To provide a comparative baseline for future studies of oral pathology in domestic livestock and to better understand connections between lesion prevalence and biological context in past animal populations.

Materials: Over 1600 sheep and cattle mandibles recovered from archaeological sites in England between 500 and 1300 CE.

Methods: A comprehensive investigation of periodontal disease was conducted based on four characteristics: dental calculus; periosteal new bone formation; alveolar recession; and ante-mortem tooth loss. The anatomical position and severity of these lesions were quantified and correlated against the age of each individual.

Results: Two types of periosteal new bone formation were recognized: one in the growing mandibles of young animals, the other in older animals and associated with disease. The incidence of calculus and alveolar recession increase with age. Correlations exist between calculus, alveolar recession and periosteal new bone formation. Disruption caused by the eruption of the P4 is also implied as a contributory factor to the onset of periodontal disease.

Conclusions: When interpreting periodontal disease in zooarchaeological collections it is vital to consider the effect of age as well as environmental and genetic factors.

Significance: This is the first comprehensive zooarchaeological study to investigate the effect of age on periodontal disease. It provides a better understanding of the frequency and presentation of periodontal disease as a baseline for future studies.

Limitations: Cattle mandibles are under-represented due to poor survival. Ideally, radiographs of mandibles with ante-mortem tooth loss would be taken, but this was not possible.

Suggestions for further research: The role of genetic factors, diet and environment needs to be better understood.

1. Introduction

Oral lesions are among the most common types of pathology reported in archaeological assemblages of animal bone (Murphy, 2005, Fig. 7). Understanding what these data mean in terms of past human-animal relationships requires comparison with baseline frequency data, understood within a biological and environmental context. This is necessary to understand whether the lesions observed in archaeological samples reflect 'normal' biological phenomena (e.g. associated with the age profiles of the herd) or the specificities of how people managed livestock in the past. While clinical studies of oral pathology in contemporary livestock populations provide useful comparanda (e.g. Aitchison 1984, Spence 1980, Thurley, 1987), their

reliability for past populations is questionable, due to a combination of genetic selection for fast growth rates, younger slaughter ages, controlled feeding regimes, preventative health treatments and agrotechnological interventions. Indeed, certain types of periodontal disease – the focus of this study – are strongly linked to modern agricultural methods and are not observed in the past (Miles and Grigson, 1990, 559; see Section 1.1). In addition, modern clinical data are not always collected in a way that is useful for comparison with archaeological datasets (e.g. Al Sadi and Younis, 2010). For this reason, the methodical analysis of pathology in large samples of animal bone from archaeological sites has been recommended as an alternative way forward (e.g. Thomas and Johannsen, 2011, 43).

In this paper, observations of zooarchaeological lesions associated

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<https://doi.org/10.1016/j.ijpp.2021.02.002>

Received 1 May 2020; Received in revised form 1 February 2021; Accepted 12 February 2021

Available online 27 February 2021

1879-9817/© 2021 The Author(s).

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with periodontal disease in over 1600 cattle and sheep mandibles from medieval England are described to better understand the presentation of this disease in the past. Systematic surveys of periodontal disease in archaeological assemblages are rarely undertaken and individual cases continue to be reported without meaningful quantification or reference to the biological context. There are a small number of notable exceptions, which have focussed on individual sites or macro-regional, millennia-spanning trends:

- [Haimovici and Haimovici \(1971\)](#): Late Neolithic to Iron Age Romania. Of 4200 fragmentary tooth rows, 11 cases of periodontal disease were recorded in sheep(6), red deer(2), cattle, pig and horse. It was suggested that the prevalence in domesticates had no singular causal factor, but was associated with husbandry practices.
- [Levitan \(1977\)](#): Medieval Wicken Bonhunt, Essex. Of 260 sheep mandibles c.148 had signs of periodontal disease. This largely methodological paper relates periodontal disease to juvenile animals with erupting teeth.
- [Levitan \(1985\)](#): Late Iron Age to Roman West Hill, Uley, Gloucestershire. A methodological paper using archaeological data from 1855 sheep mandibles to test a recording protocol, identifying eruption of the permanent premolars as a major contributing factor to periodontal disease.
- [Bartosiewicz \(2008\)](#): Neolithic sites in Central Europe and the Near East. Fifty incidences of periodontal disease came from an unrecorded number of sheep and goat mandibles. The author concludes that sheep are more susceptible to periodontal disease than goats, with other contributing factors including over-crowded stocking and varying quality of fodder or graze.

These studies provided vital methodologies and insights into the possible aetiologies. However, they are limited in their discussion of the inter-relationships between oral lesions and investigation into the effect of age on periodontal disease. This study adds to this restricted corpus, covering 1100 years of sheep and cattle husbandry from England. The ambition is to provide a better understanding of the frequency and presentation of periodontal disease as a baseline for future studies, rather than investigating changing disease incidence through time. To this end, we will address five research questions:

- 1 How do oral pathologies associated with periodontal disease (calculus, new bone formation, alveolar recession and ante-mortem tooth loss) manifest in zooarchaeological material?
- 2 How is the presence and severity of oral pathology affected by age and taxon?
- 3 What is the relationship between dental calculus, alveolar recession, periosteal new bone formation and tooth loss?
- 4 What can be deduced regarding the likely causal factors of periodontal disease?
- 5 How can the findings inform future recording and analysis of periodontal disease in past animal populations?

1.1. The biology of periodontal disease

Periodontal disease is routinely (if inconsistently) recorded in domestic livestock from archaeological sites (e.g. [Dobney et al., 2007](#); [O'Connor, 1982](#); [Wilson et al., 1978](#)), with significant potential for informing upon animal management in the past because of its strong association with diet and pasture quality. The disease is characterised by chronic inflammation of the periodontium (gingiva, periodontal ligament, alveolar bone and cementum) and usually escalates from inflammation of the gingiva (gingivitis) following the accumulation of bacteria-rich dental plaque. Other predisposing factors include genetics, abnormal tooth eruption and wear, saliva production, impacted food or other debris between the tooth and gingiva causing damage to the

periodontal ligament and localised inflammation, grazing on depleted pastures, and malnutrition ([Aitchison and Spence, 1984, 136](#); [Anderson and Bulgin, 1984](#); [Baker and Brothwell, 1980, 153–154](#); [Erjavec and Crossley, 2010, 299](#); [Hillson, 2005](#); [Page and Schroeder, 1982](#)). It is widely acknowledged that the incidence of periodontal disease increases with age ([Bartosiewicz and Gál, 2013, 182](#); [Dvorak et al., 2009](#); [Miles and Grigson, 1990, 524](#)).

The progression of periodontal disease is summarised in [Table 1](#), along with possible manifestations in the underlying bone that may be observed in zooarchaeological mandibles. It should be noted that, although plaque does not survive in the archaeological record, mineralised plaque (calculus) formations are commonly observed, and can be used as a proxy for plaque deposits.

The disease causes discomfort and can, in severe cases, reduce food intake sufficiently to result in secondary malnutrition (e.g. [Anderson and Bulgin, 1984](#); [Britt and Baker, 1990, 139](#); [Silva et al., 2016](#)). Chronic bacteraemia of periodontal disease can also be associated with pathology beyond the oral cavity (e.g. kidney, liver and heart) and thus affect animal health more broadly (e.g. [DeBowes et al., 1996](#); [Hirschfeld and Kawai, 2015](#); [Li et al., 2000](#)).

In sheep, periodontal disease is recognized in two forms, although both are symptoms of the same disorder. The first affects the incisors, commonly known as 'broken mouth', and the second affects the premolars and molars ([Miles and Grigson, 1990, 557](#); [Page and Schroeder, 1982, 180](#)). Broken mouth is widely described as a modern phenomenon ([Hitchin, 1948, 251](#); [Miles and Grigson, 1990, 559](#)), and it is not commonly recorded in cattle. Incisors are rarely recovered within the mandibles of cattle and sheep in the archaeological record ([Hillson, 2005, 231](#)), so this investigation focuses solely on the cheek teeth (premolars and molars).

2. Materials and methods

An increase in agricultural production occurred in England between the 6th and 13th centuries AD, requiring expansion of arable land to feed a growing population ([Hamerow et al., 2019, 2020](#)). A recent project investigating the timing and causes of this change relative to animal husbandry included the systematic recording of lesions associated with periodontal disease. Just over 1600 mandibles from thirteen sites occupied between AD 400 and 1500 were recorded in the study at the time of writing ([Table 2](#)). The majority of specimens came from sheep, largely due to greater fragmentation of cattle mandibles resulting variously from post-depositional breakage and different butchery practices affecting sheep and cattle ([Holmes, 2011, 87](#)). A greater proportion of sheep mandibles are from juvenile animals ([Table 2](#)). This does not

Table 1

Traditional progression of periodontal disease ([Hillson, 2005](#); [Miles and Grigson, 1990, 521–523](#); [Page and Schroeder, 1982](#); floating; [Uzal et al., 2016, 11–12](#)).

Progression	Zooarchaeological manifestation
Build-up of plaque and bacteria	Calculus formation
Inflammation of the gingiva, pocket formation, increasing exposure to micro-trauma and pathogens	Periosteal new bone formation in response to inflammation
Spread of inflammation/infectious agents to the periodontal ligament and alveolar bone	Alveolar recession, continuing as the disease progresses
Destruction of periodontal ligament due to the impact of inflammation on collagen fibres; inflammation and resorption of alveolar bone	Pitting and widening of the alveolar margin, continuing as the disease progresses
Alveolar pocketing and the subsequent loosening of the tooth, which may cause drifting and atypical tooth wear	Loosening of the tooth, continuing as the disease progresses
Ante-mortem tooth loss	Tooth loss
Remodelling and recovery of the alveolar bone	Infilling of the alveolus and replacement with new bone

Table 2

Number of mandibles included in the study, by site. %Juv = proportion of juvenile mandibles exhibiting deciduous dentition (stages A to E).

Site	Period (AD)	County	Cattle	%Juv	Sheep	%Juv
28 Bow Street, London	600–750	Middlesex	18	60	22	77
Barking Abbey	675–1500	Middlesex	8	60	12	70
Cadley rd, Collingbourne Ducis	700–900	Wiltshire	10	60	43	73
Cook Street	700–875	Hampshire	23	45	26	50
Eynsham	500–1330	Oxfordshire	108	25	171	60
French Quarter, Southampton	900–1350	Hampshire	107	22	147	49
High Street, Ramsbury	750–850	Wiltshire	28	38	42	56
Ketton	850–1066	Northamptonshire			2	100
Lyminge	400–1200	Kent	65	51	165	65
Market Lavington	400–1400	Wiltshire	44	61	68	72
Stafford	900–1300	Staffordshire	8	33	22	61
Stoke Quay, Ipswich	700–1500	Suffolk	72	57	152	64
Stratton, Biggleswade	600–1350	Bedfordshire	72	24	176	62

adversely affect the study, as much of the current analysis incorporates age as a variable. This data will be used to investigate the effects of biological variables on the prevalence and severity of oral pathologies and the inter-relationships between them, rather than a detailed consideration of the effect of changing husbandry methods through time.

Detailed observations of calculus formation, alveolar recession, new bone formation and ante-mortem tooth loss in cattle and sheep mandibles were recorded, providing a dataset for investigating the inter-relationships of multiple variables. Cattle and sheep mandibles with at least two cheek teeth (second premolar to third molar) were included in the database and the following criteria were applied:

- Although morphologically the teeth of sheep and goats are similar, where distinctions could be made (Zeder and Pilaar, 2010), goat mandibles were excluded.
- Eruption of individual teeth and subsequent wear of the occlusal surface were recorded after Payne (1973) and Grant (1982) and summed for each mandible (Mandible Wear Score). These scores were then used to calculate mandibular wear stages based on Jones (2006) for sheep (stages A–J) and Jones and Sadler (2012) for cattle (stages A–K) (Table 3).
- The presence and severity of calculus formation was recorded for each tooth (0= none; 1= slight; 2= moderate; 3= considerable) (Fig. 1).
- Periosteal new bone formation was recorded as present/absent on the mandible in the region below each tooth (0= none; 1= present) (Fig. 2).
- Alveolar recession was recorded in the area adjacent to each tooth, using the six-point scale devised by Levitan (1985) (Table 4). A score of 0= no change.

As the data are non-parametric, Spearman's r^s was used to test correlations between variables, and a Kruskal-Wallis test to investigate inter-site variation. The PALaeontological STatistics software package

(Hammer et al., 2001) was used for these calculations. Abbreviations used are: dp2, dp3, dp4 for deciduous premolars; P2, P3, P4 for permanent premolars; M1, M2, M3 for molars and PNB for periosteal new bone. The cheek teeth of ungulates erupt in the following pattern: deciduous premolars dp2-dp3-dp4; permanent molars M1-M2-M3; permanent premolars P2-P3-P4. The permanent premolars replace the deciduous premolars, so the P2 will erupt into the alveolus of the dp2, the P3 into the alveolus of the dp3 and the P4 into the alveolus of the dp4. There are no deciduous precursors to the permanent molars, so they erupt through new bone. Fig. 3 illustrates the major mandibular structures referred to in the text.

3. Results

3.1. Alveolar recession

The low incidence of alveolar recession associated with deciduous teeth (Fig. 4 and Table 5) is consistent with findings from Thurley (1987, 382), who describes only mild gingivitis in the area of these teeth in live animals. There is a statistically significant increase in the prevalence of alveolar recession in older animals (Fig. 5 and Table 6), particularly sheep at minimally wear stage E and above, and cattle minimally at wear stage F are more likely to develop periodontal disease (see Table 3 and method for a description of age stages).

Alveolar recession is most commonly observed in the area of the P4, M1 and M2 (Fig. 4), which is consistent with the anatomical distribution noted in previous archaeological studies (Bartosiewicz and Gál, 2013, 178; Levitan, 1985, 52). In cattle, it is most commonly associated with the M1, and infections affecting the adjacent teeth (M2 and P4) most likely spread from the M1. This is not surprising, as the M1 remains in the mouth for the longest time (Table 7). Accordingly, studies in living sheep have also found that periodontal disease is most likely to affect the mandibular M1, with very deep pockets occurring in the soft tissue (a precursor to periodontal disease) between the P4 and M1 in over 61 % of all animals in one study (Aitchison and Spence, 1984, 292). However, in

Table 3

Mandible wear stages and approximate corresponding age in months from the most commonly cited sources for cattle and sheep at known age. The range of Mandible Wear Scores based on Grant (1982) are also provided.

Wear stage	Sheep			Cattle			
	Jones (2006)	Payne (1973)	Greenfield and Arnold (2008)	Grant MWS	Halstead (1985)	Jones and Sadler (2012)	Grant MWS
A	<1	0–2	0–2	1–2	0–1	0	1–3
B	1–3	2–6	2–6	3–7	1–8	0–6	4–6
C	3–12	6–12	6–12	8–18	8–18	5–18	7–16
D	10–24	12–24	12–24	19–28	18–30	16–28	17–30
E	23–36	24–36	24–36	29–33	30–36	26–36	31–36
F	36–66	36–48	36–48	34–37	Young adult	34–43	37–40
G	66–96	48–72	48–72	38–41	Adult	40–78	41–43
H	96–120	72–96	72–96	42–44	Old adult	60–120	44–45
I/J	>120	96–120	96–120	>45	Senile	72–192	>46
K	–	–	–	–	–	168–240	–

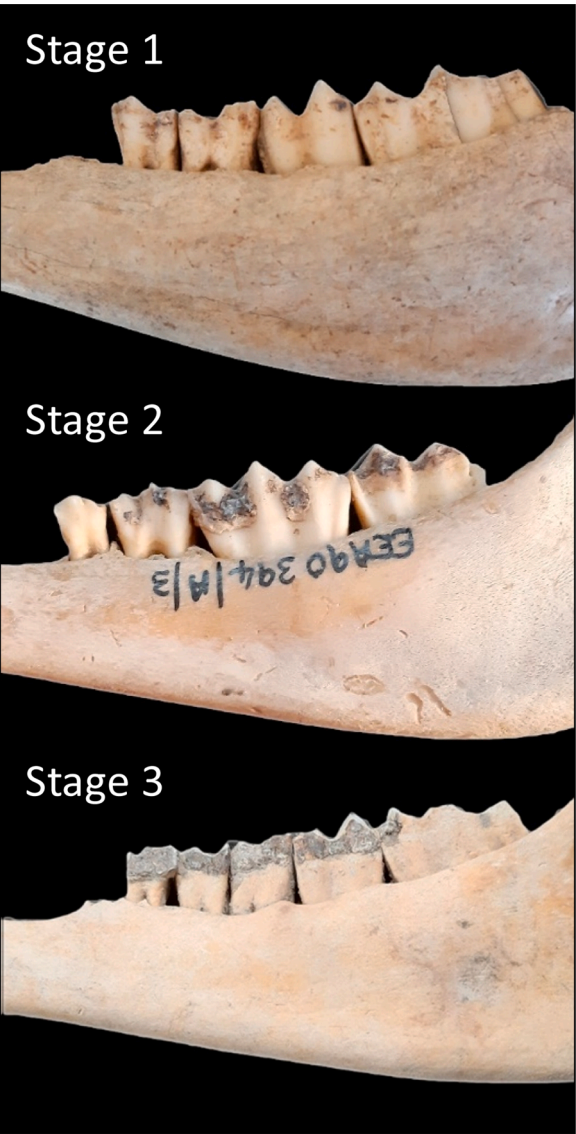


Fig. 1. Recording system for dental calculus. 1= slight calculus visible usually on one side of the tooth; 2= moderate calculus build up, usually on both sides of the tooth; 3= considerable calculus build up that is beyond the contour of the tooth.



Fig. 2. Periosteal New Bone formation on a cattle mandible (buccal view). PNB types 1 and 2 manifest in the same way. See text for distinctions.

the archaeological dataset, the P4 is more commonly affected by alveolar recession in sheep (Table 5), and possible reasons for this discrepancy are considered further in section 4.1.

Table 4
Recording protocol for periodontal disease (Leviton, 1985).

Code	Definition
0	no change – normal mandibular bone
1	recession of alveolar margin only; no widening of the alveolus
2	alveolus widened out, tooth loosened, pitted margins, more recession
3	ante-mortem tooth loss and first stages of alveolus infilling
4	infilling advanced but not complete
5	new bone formation nearly complete

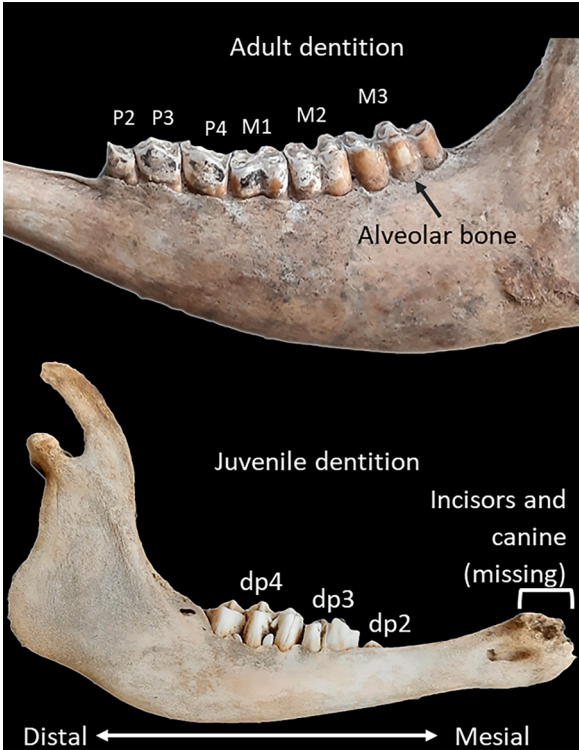


Fig. 3. Illustration to show basic structures of the juvenile and adult mandible referred to in the text (buccal view). Deciduous premolars are each replaced by the adult counterpart. Please note zooarchaeological conventions describe deciduous molars as premolars (dp); M = permanent molars.

3.2. Calculus

Dental calculus was commonly observed on all sheep and cattle teeth (Fig. 4 and Table 5). It is more frequently recorded on the permanent premolars than any other teeth, which is particularly notable in cattle. The morphology of the premolars means that there are more folds for plaque to form and become trapped than on the smoother surface of the molars. The incidence of calculus increases with age and is statistically significant (Table 6 and Fig. 5) in both cattle and sheep.

3.3. Periosteal New Bone (PNB) formation

Two types of PNB were discerned, the first (Type 1) was observed in the growing mandibles of young animals, while the second (Type 2) was observed in older animals. Type 1 is most common and occurs in the area below the deciduous premolars and erupting permanent molars (Figs. 4 and 6). There is a negative correlation between age and the incidence of Type 1 PNB (Table 3), consistent with its presence in the growing mandibles of younger animals at wear stages A to E, when the teeth are still erupting (Fig. 5).

Type 2 PNB formation is observed occasionally in the area below the permanent dentition of older cattle and sheep (Figs. 4 and 6). It is more

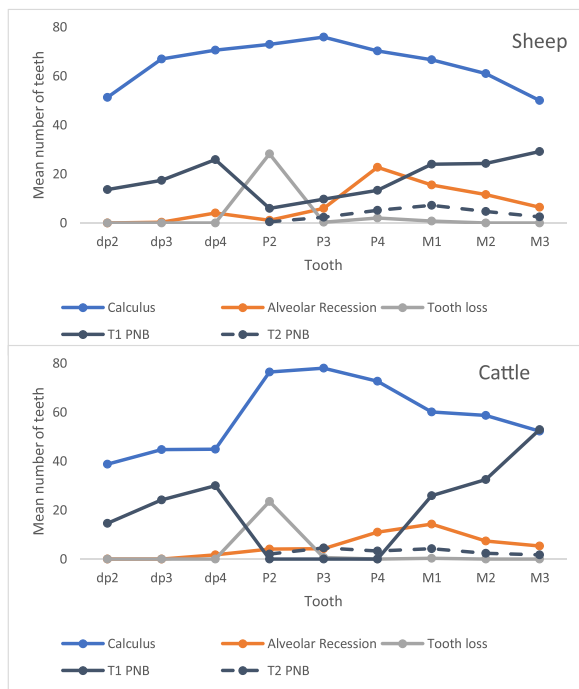


Fig. 4. Relationship between specific tooth and incidence (presence) of lesions.

localised than Type 1 PNB and is directly associated with an area of inflammation or infection. Any mandible from an animal over wear stage E should not be affected by Type 1 PNB resulting from growth, as all teeth are erupted and in wear. The high value of PNB in cattle at wear stage F was not observed in sheep and was further investigated. Of the thirteen mandibles at wear stage F, PNB was observed in three, of which two also had alveolar recession in the same area of the mandible, so the PNB observed in these cases is likely to be related to infection associated with alveolar recession. With the exception of the cattle mandibles at wear stage F, an increase in the number of mandibles with PNB can be observed in old adult and elderly sheep at wear stages G, H and I and cattle at H and K (Fig. 5) that reflect pathology rather than bone

modelling. This produces a significant correlation in both sheep and cattle mandibles (Table 6), although not as strong in cattle, due to the high proportion of mandibles at wear stage F exhibiting Type 2 PNB.

3.4. Ante-mortem tooth loss

Very few mandibles were recorded with teeth that could definitively be identified as lost ante-mortem. The difference between post-depositional tooth loss and ante-mortem tooth loss prior to healing cannot be easily discerned. Therefore, only teeth that had been lost long enough for the alveolar cavity to begin remodelling were included in this category. Ante-mortem tooth loss is most likely to affect the P2 (Table 5 and Fig. 4), with very few other teeth lost from cattle mandibles, and the P4 and M1 occasionally missing from sheep mandibles. There is an increase in tooth loss with age (Fig. 5), which is statistically significant for sheep (Table 6).

3.5. Relationship between lesions

As described in Section 1.1, numerous studies make the case for the excess build-up of calculus as a causal factor of periodontal disease (Bartosiewicz, 2008, 8; Bartosiewicz and Gál, 2013, 178; Hillson, 1979; Levitan, 1985, 44; Spence et al., 1980, 289). This is demonstrated by a statistically significant co-association between mandibles with signs of calculus and alveolar recession (regardless of severity) in both cattle and sheep (Table 8), the strength of this relationship increasing from the M3 to P4 (Fig. 7). While calculus is therefore a causal factor, its presence does not inevitably lead to periodontal disease, as calculus was recorded in 78 % of sheep and 67 % of cattle mandibles, yet alveolar recession was only recorded in 18 % and 13 % respectively (Table 9). This has been observed previously (Levitan, 1977, 43), and is not unexpected if calculus precedes periodontal disease, only adversely affecting oral health when excessive accumulations occur.

A more surprising observation is made when the severity of calculus and alveolar recession are plotted (Fig. 8). The greatest severity of dental calculus is observed in the permanent premolars, yet it is the P4, M1 and M2 that are subject to the most severe forms of alveolar recession. If calculus was the major cause of periodontal disease, the premolars might be expected to exhibit greater levels of alveolar recession. It is possible that this frequency may be affected by the absence of the P4, M1

Table 5

Summary of data for individual teeth and mandibles. Total = total number available; N = total number exhibiting change; Score = total score where relevant.

Sheep	Alveolar recession			Calculus			PNB Type 1		PNB Type 2		Tooth loss	
	Total	N	Score	Total	N	Score	Total	N	Total	N	Total	N
dp2	327	0	0	162	83	122	243	33			146	0
dp3	345	1	2	285	191	331	259	45			301	0
dp4	350	14	15	336	237	392	275	71			353	0
P2	459	5	19	85	62	117	117	7	209	1	149	42
P3	475	28	37	344	261	513	123	12	217	5	405	1
P4	511	116	165	398	280	486	135	18	232	12	454	9
M1	828	128	188	770	513	801	421	101	252	18	817	6
M2	694	81	107	629	384	580	324	79	274	13	736	0
M3	486	31	39	442	221	334	178	52	276	7	560	0
Mandible	1007	177	572	1036	805	3676	468	194	287	34	546	25
Cattle	Alveolar recession			Calculus			PNB Type 1		PNB Type 2		Tooth loss	
	Total	N	Score	Total	N	Score	Total	N	Total	N	Total	N
dp2	103	0	0	67	26	38	55	8			70	0
dp3	110	0	0	94	42	55	58	14			89	0
dp4	113	2	2	118	53	81	70	21			125	0
P2	195	8	20	72	55	88	6	0	99	2	102	24
P3	212	9	14	145	113	184	7	0	110	5	186	1
P4	220	24	35	161	117	191	7	0	121	4	188	0
M1	321	46	65	278	167	236	89	23	144	6	292	1
M2	296	22	25	264	155	207	80	26	175	4	295	0
M3	266	14	14	247	129	166	53	28	181	3	284	0
Mandible	520	68	175	546	365	1246	126	59	206	11	546	25

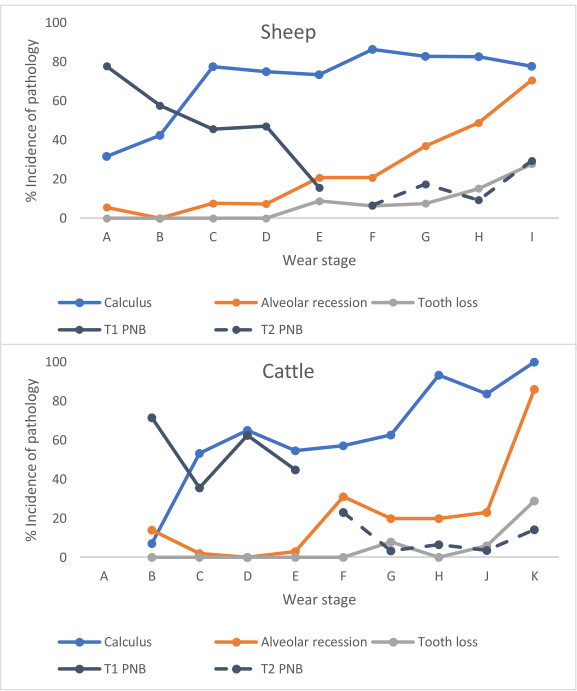


Fig. 5. Relationship between age (wear stage) and incidence (presence) of lesions. See Table 3 for an explanation of wear stages.

Table 6
Correlation between age (wear score of each tooth) and score of various dental lesions for each tooth using Spearman's r^s . Shaded cells = statistical significance.

	Sheep		Cattle	
	r value	P	r value	P
Calculus	0.3213	<0.0001	0.4365	<0.0001
Alveolar Recession	0.3655	<0.0001	0.3474	<0.0001
PNB Type 1	-0.5012	<0.0001	-0.5094	<0.0001
PNB Type 2	0.1797	0.0064	0.1739	0.0297
Tooth loss	0.1866	<0.0001	0.1351	0.0683

Table 7
Length of time various teeth are in wear (teeth that remain in wear for life – over ten years for sheep and 14 years for cattle – are represented by +, m = months).

Tooth	Sheep			Cattle		
	Deniz and Payne (1979)	Jones (2006)	Davis (2000)	Jones and Sadler (2012)	Legge (1992)	Brown et al. (1960)
dp2	0–22m			0–28m		0–30m
Dp3	0–22m			0–28m	1–36m	0–30m
Dp4	0–22m	0–22m	0–24m	0–36m	1–36m	0–36m
P2	21m+			28m+		24m+
P3	21m+			28m+	26m+	28m+*
P4	21m+	22m+	26m+	36m+	26m+	30m+
M1	3m+	4m+	<8m+	5m+	6m+	5m+
M2	11m+	10m+	10m+	16m+	15m+	12m+
M3	25m+	19m+	22m+	26m+	26m+	24m+

*Tables of eruption record the P3 at 18months, but careful reading of the source material suggests that this was an error, and it should have been 28 months.

and M2 in the most severe cases of alveolar recession that lead to ante-mortem tooth loss. However, the numbers of lost teeth are so small that it is unlikely to affect the severity of calculus recorded. However, a significant, positive correlation exists between Type 2 PNB and alveolar recession, which argues for an important synergistic role of inflammation in the reactive change and remodelling of bone in periodontal

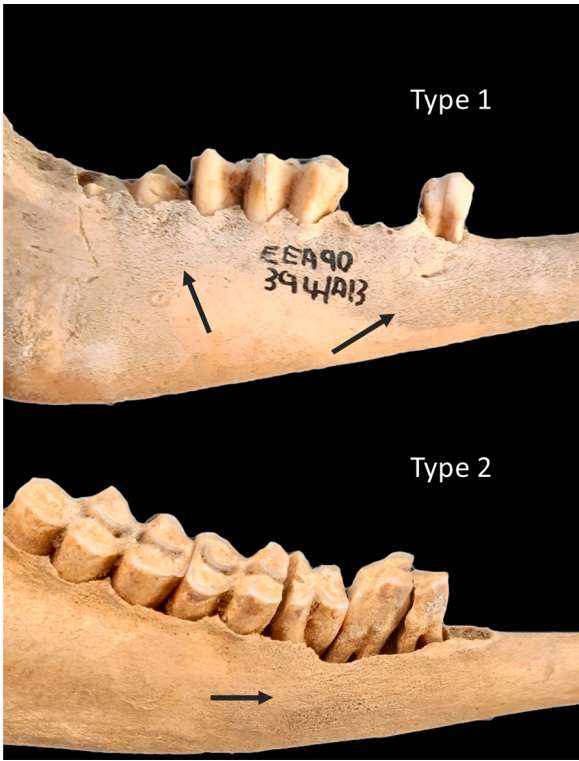


Fig. 6. Sheep mandibles (buccal view) illustrating Type 1 periosteal new bone formation, associated with growing mandibles, and Type 2, associated with oral pathology.

disease in sheep and cattle (Table 8).

3.6. Inter-taxa variation

Periodontal disease is often quoted as being more prevalent in sheep than other animals (Bartosiewicz and Gál, 2013; Davies, 2005, 80; Uzal et al., 2016, 11). However, the results of this study reveal a similar proportion of mandibles affected in terms of both prevalence and severity of lesions (Table 9). This indicates that oral pathologies affect cattle and sheep in similar ways.

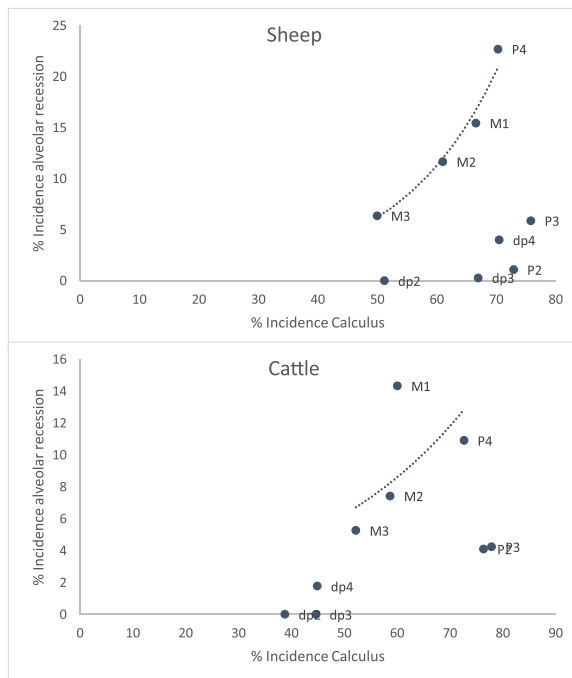
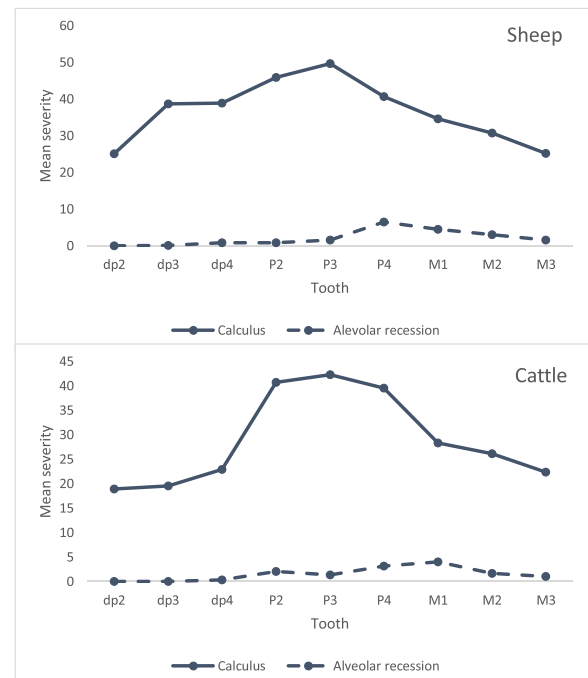
3.7. Inter-site variation

Localised factors that lead to differences in the occurrence and severity of periodontal disease observed between farms have been identified in modern live studies. In the investigations of Spence et al. (1980) and Thurley (1987), results varied significantly between farms even when animals of the same age and breed were compared. Differences in oral morphology between breeds can affect the nature of occlusion of the teeth, which has been shown to influence the propensity of different breeds to develop periodontal disease (Hitchin, 1948). Increased periodontal disease in cattle and sheep has been observed to be dependent on the type of pasture, which again may lead to inter-farm differences (Miles and Grigson, 1990, 561; Silva et al., 2016). As described previously (Section 1.1), other factors include genetic disposition, environmental conditions such as the geology of a site, availability of water and quality of forage and differences in husbandry such as the feeding of hay or grain. There is little consensus in existing studies regarding the effect of these factors.

To test the findings in a practical context, the methods were applied to several case study sites. A sub-set of assemblages dated between AD 650–850 (Fig. 9), was investigated in detail for differences in ante-mortem tooth-loss and the severity of calculus and alveolar recession. A restricted date-range was included to reduce the likelihood that the

Table 8Test for correlation between mandibular lesions using Spearman's r^s . Shaded cells = statistical significance.

Sheep	Calculus	T2 PNB	Alveolar recession
Calculus		0.0002	<0.0001
T2 PNB	0.13429		<0.0001
Alveolar recession	0.25618	0.31653	
Cattle	Calculus	T2 PNB	Alveolar recession
Calculus		0.0354	0.0091
T2 PNB	0.11692		<0.0001
Alveolar recession	0.14457	0.29181	

**Fig. 7.** Relationship between calculus and alveolar recession.**Fig. 8.** Mean severity of calculus and alveolar recession affecting cattle and sheep teeth. Severity calculated as the total score/ maximum possible score.**Table 9**

Proportion of lesions affecting all cattle and sheep mandibles. See method for scoring system.

	Cattle		Sheep	
	Prevalence	Severity	Prevalence	Severity
Calculus	67 %	29 %	78 %	36 %
Alveolar Recession	13 %	2%	18 %	3%
PNB Type 1	47%	20 %	41 %	17 %
PNB Type 2	5%	3%	12 %	4%
Tooth Loss	5%		5%	

Prevalence= (N mand with path/ Total N mand)*100.

Severity= (Total path score/ Total possible score)*100.

results would be less affected by different husbandry strategies. During the period AD 650–850 in England the majority of sites were self-sufficient, producing cattle and sheep largely for meat, with some small-scale surplus production and a few older animals kept for secondary products such as milk, wool and traction (Holmes, 2014; O'Connor, 2010). Documentary evidence for animal husbandry in this period is scarce, although it is likely that some fodder was provided to cattle and sheep during the winter months. There was less restriction on grazing than occurred later in the medieval period when more land came under arable cultivation (Banham and Faith, 2014, 284), so pasture was likely to have been good quality for the local area. This group of sites

also provided a large sample size.

Statistically significant inter-site variation exists for calculus scores for sheep ($H(\chi^2) = 118.3$, $p < 0.0001$) and cattle ($H(\chi^2) = 22.07$, $p = 0.0006$) and for sheep alveolar recession scores ($H(\chi^2) = 11.6$, $p = 0.0002$), but not for cattle, as the samples were too small. As results were not uniform between sites, it implies they were subject to some site-specific variables.

To explore this, the results of the case studies were used to investigate inter-site variation in terms of animal husbandry models for each site. It has been determined that older animals will tend to have a greater incidence of calculus and alveolar recession, so it is vital to ensure that sites with a focus on secondary products (i.e. older animals) are not being compared directly with those that produce animals for meat (i.e. younger animals). Scores of calculus and alveolar recession for sheep mandibles are therefore presented for three case study sites by wear stage, so that the effect of age can be mitigated. The sites of Collingbourne, Wiltshire; Cook Street, Southampton and Eynsham Abbey, Oxfordshire were chosen as they provide large samples with varied models of sheep husbandry. Collingbourne had a high proportion of young sheep culled for meat at wear stages C and D (Fig. 11); at Southampton sheep were older, most being culled between wear stages E and G; while at Eynsham there were two peaks in the mortality data, at stages C and D and F and G, the latter two sites including a combination of younger sheep kept for meat, and older animals used for milk and/ or

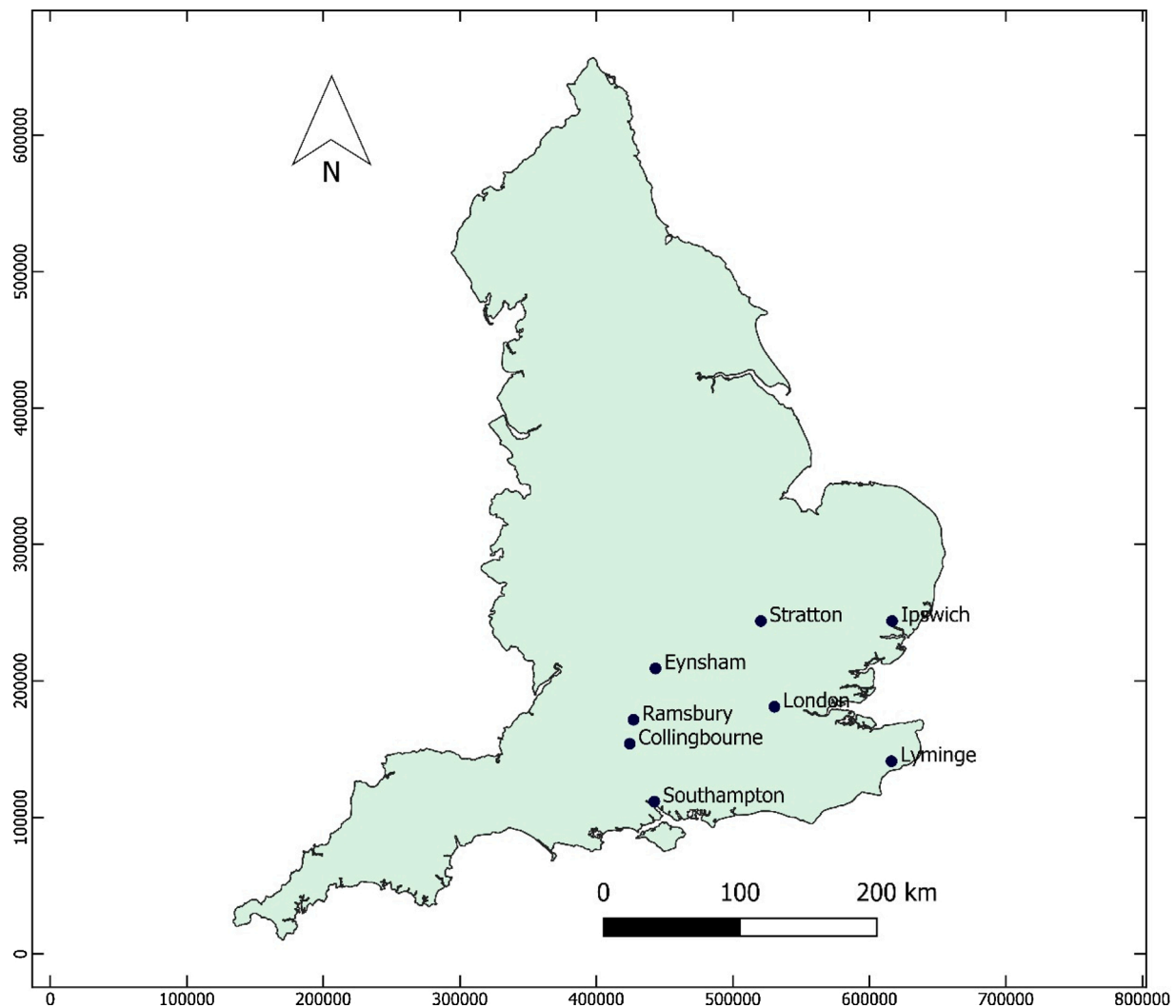


Fig. 9. Location of sites included in the inter-site analysis.

wool. Scores for alveolar recession increase in older animals, as predicted (Fig. 10), but are considerably greater at Collingbourne, and very low at Southampton and Eynsham. Calculus scores are extremely varied between sites (Fig. 11). While the Collingbourne data follow the expected pattern by increasing with age, those for Southampton decrease with age, and at Eynsham remain relatively stable.

4. Discussion

The results will be further explored to better understand causal factors, incorporating the findings from previous studies and taking into account discrepancies between cattle and sheep data, and modern studies.

4.1. Alveolar recession

Live studies and data from archaeological cattle mandibles presented here all indicate that alveolar recession is more likely to affect the M1. This contrasts with the evidence presented for sheep, which indicates that the P4 is most often affected. This was investigated further by tabulating the scores of individual mandibles that were recorded with the areas surrounding both the P4 and M1 intact (Table 10), which revealed that alveolar recession was usually recorded at the same stage for both the M1 and P4, so the discrepancy was not due to the disease beginning at the P4 and moving to the M1. It is also unlikely to be caused

by length of time the tooth is present in the mandible, as the M2 erupts considerably earlier than the P4 in sheep (Table 7) but exhibits less severe alveolar recession. The absence of a co-association between calculus and alveolar recession (Section 3.5) also implies that other factors influence the onset of periodontal disease.

The cause is more likely to be that described by Levitan (1977, 40; 1985, 51), who suggests that the relatively large size of the dp4 alveolus, into which the smaller P4 erupts (Fig. 12) may have some impact on the development of periodontal disease, presumably following the introduction of infection or debris into the alveolus. He suggests that the process of eruption acts as a 'catalyst' for the onset of periodontal disease. This may be particularly pertinent if the area of the M1 is liable to form deep pockets prior to the loss of the dp4, which would create a reservoir for infection as the P4 erupts. This hypothesis is supported by the increases incidence of alveolar recession in sheep at wear stage E and cattle at wear stage F (Fig. 5), which corresponds to the period when the P4 erupts and comes into wear (Jones, 2006; Jones and Sadler, 2012).

4.2. Calculus

Supporting the finding of previous studies (Dobney and Brothwell, 1986, figs. 4.4 and 4.5), dental calculus is more commonly observed in the permanent premolars of cattle and sheep. In the veterinary literature, it has been suggested that calculus deposits are greatest in areas adjacent to salivary ducts (Uzal et al., 2016, 9), yet in cattle and sheep

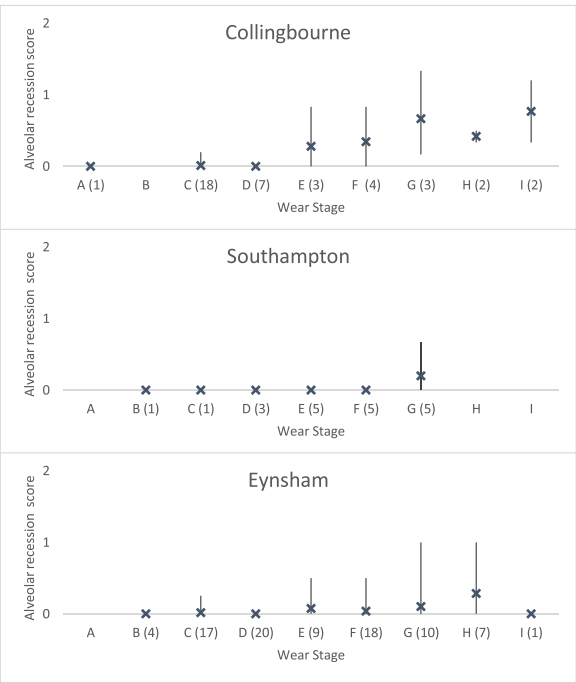


Fig. 10. Minimum, maximum and mean scores of alveolar recession (total score for each mandible/ number of teeth) in sheep mandibles from three different sites. (n)= number of mandibles at each wear stage.

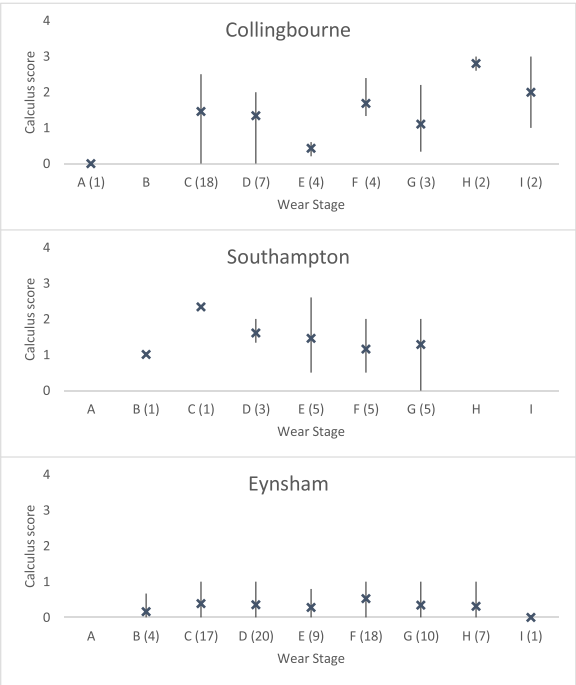


Fig. 11. Minimum, maximum and mean scores of calculus (total score for each mandible/ number of teeth) in sheep mandibles from three different sites. (n)= number of mandibles at each wear stage.

this seems unlikely. The sublingual glands are diffuse and drain in the area of the cheek teeth, while the parotid duct opens in the area of the M2, which is less affected than more mesial teeth (Ducharme et al., 2016). Furthermore, in sheep the incidence of calculus recorded on the premolars and molars in the middle of the tooth row is similar, suggesting that there is no localised cause.

Table 10
Alveolar recession scores for sheep P4 and M1 in individual mandibles where the alveoli of both teeth are present. Shaded cells = mandibles where the P4 and M1 are affected to the same extent.

P4 score	M1 score					
	0	1	2	3	4	5
0	-	12	8			
1	15	53	7	1	1	
2	1	2	23	2	1	
3	2	1	4	3		
4						
5						

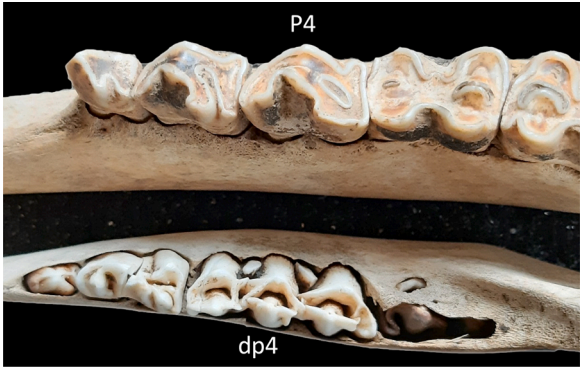


Fig. 12. Cattle mandibles (occlusal view) showing the relative difference in size of the P4 (top), which erupts into the larger alveolus of the dp4 (below). Mandibles shown at the same scale.

4.3. Periosteal New Bone Type 1

Mild inflammation, or gingivitis, of the soft tissues surrounding erupting teeth is commonly observed in living populations (Brown et al., 1960, 13; Spence et al., 1980; Thurley, 1987). Inflammation of the gingiva can spread to the mandibular periosteum, stimulating its bone formation properties (Bartosiewicz and Gál, 2013, 93) and causing the recorded high incidence of PNB in growing mandibles. This has been observed in a study investigating the structure of mandibular bone in sheep of different ages (Atkinson et al., 1982, 59). Permanent premolars are not affected to the same extent, as they erupt into existing alveoli, and there is little growth required to accommodate them. It is notable that this form of PNB is resorbed with Haversian remodelling in older animals and does not continue to be observed once the mandible has stopped growing (Atkinson et al., 1982, 63).

4.4. Ante-mortem tooth loss

The archaeological findings are somewhat at odds with the work of Aitchison and Spence (1984), who found that the incidence of tooth loss decreases gradually from the P2 to M3 (Aitchison and Spence, 1984, fig. 2). All cases of ante-mortem tooth loss of the P3, P4 and M1 are related to advanced stages of periodontal disease (Table 11), where resorption of the alveolar bone and ligaments holding the tooth in place lead to tooth loss and subsequent remodelling of the alveolar bone. The low incidence of tooth loss in the molars reflects findings from live studies where the cheek teeth tend to remain in the mandible even when all incisors have been lost to periodontal disease (Spence et al., 1980, 288).

The absence of the P2 is more nuanced, as only a few examples are related to alveolar recession (Table 6), which implies different causal factors for the loss of the P2 compared to the P3, P4 and M1. It is problematic to distinguish between a lost P2 where the alveolus has

Table 11

Incidence of ante-mortem tooth loss and number of mandibles where tooth loss is associated with alveolar recession (AR).

Tooth	Cattle		Sheep	
	Total N lost	N with AR	Total N lost	N with AR
dp2	0		0	
dp3	0		0	
dp4	0		0	
P2	24	1	42	4
P3	1	1	1	1
P4	0		9	9
M1	1	1	6	6
M2	0		0	
M3	0		0	

closed, and those that are congenitally absent without radiographic examination, which was beyond the scope of this study. Furthermore, the roots of the P2 are relatively shallow, and the position of this tooth at the mesial aspect of the tooth row also means that loss following trauma to the cheek or mouth cannot be excluded. Previous radiographic work on cattle and sheep mandibles has described congenital absence, where the permanent P2 failed to form, and note considerable variability in the prevalence of loss between sites and even phases within a single site (Albarella, 2019, 175; Andrews and Noddle, 1975).

4.5. Inter-site variation

Significant differences in the calculus scores of cattle and sheep, and alveolar recession in sheep mandibles have been reported from the case study sites, and further investigation showed that this was due to age-independent variables. Hillson (2005) has suggested that large-scale differences in oral pathologies are due to diet, while modern human dental studies suggest a genetic cause (Modeer and Wondimu, 2000).

The potential role of genetic factors can be illustrated using the frequencies of ante-mortem tooth loss of the P2, which is a congenital trait (Andrews and Noddle, 1975). Populations with a high proportion of absent P2 (Table 12) are particularly notable at sites in the south of the country, at Lyminge, Southampton, Ramsbury and Collingbourne (Fig. 10), which implies an inter-regional genetic difference in the sheep at these sites. It may also go some way towards explaining the differences observed in the severity of alveolar recession and calculus deposits observed at Collingbourne.

Factors relating to diet are complicated by local differences. During this period, Southampton was a *wic*, a proto-urban site, that would have been home to a population including non-agrarian workers (Crabtree, 2018) who would have required a supply of meat from the surrounding area. The animal remains from this site therefore have potential to be recovered from a wide geological area, which has little to add when considering site-specific variations. However, Collingbourne is a rural site, and Eynsham an estate centre, both of which may be expected to have consumed sheep kept on local pasture, so the specific geology at each site may influence the oral pathologies observed (assuming there was minimal redistribution of sheep between sites). Eynsham is situated

Table 12

Proportion of sheep mandibles showing antemortem loss of the P2 for middle Saxon sites, in order of increasing prevalence.

Sheep	Total N P2	% loss
London	2	0
Ipswich	8	13
Eynsham	14	14
Stratton	11	27
Lyminge	8	38
Southampton	5	40
Ramsbury	4	50
Collingbourne	5	60

on loam soils within the lowlands of the Upper Thames Valley, 74 m above sea level, while Collingbourne is on the silty soil of chalk downlands at a height of 130 m. This influences the graze available to sheep, with a greater range of hardy plants such as sheep's fescue and meadow oat grass growing on the thin soils of the downlands, compared to the lush pastures of timothy and rye grass in the Eynsham valley (Ashwood, 2014; Crofts and Jefferson, 1999; Rodwell, 1992). As noted by Bartosiewicz (2008), the quality of grass may be expected to affect the severity and incidence of periodontal disease, and this may also be a cause of greater oral pathologies observed at Collingbourne.

5. Conclusion

The results have largely served to confirm previous studies on living and archaeological populations investigating periodontal disease, as well as providing new insights regarding the role of age, inter-dependency of symptoms and population-specific factors. The major findings are summarised here:

- Calculus is commonly recorded in archaeological samples, affecting the permanent premolars more than other types of teeth, possibly related to their morphology and location in the mouth. The prevalence of calculus increases with age.
- Manifestations of PNB measure two phenomena: Type 1, found only in young animals, where PNB is laid down as a response to tooth eruption and growth of the mandible; Type 2, new bone growth as a reaction of bone to infection, which is commonly associated with areas of alveolar recession.
- The loss of the P2 is not unusual in cattle and sheep populations and is often likely to be a congenital trait. Ante-mortem tooth loss as a result of periodontal disease is observed on a few P2, and all P3, P4 and M1 teeth. Tooth loss increases in older animals.
- Alveolar recession most commonly affects the M1 and P4 and, less commonly, the M2. Again, this is a problem that increases in prevalence with age, only rarely affecting animals with juvenile dentition.
- Greater accumulations of calculus correlate to an increase in alveolar recession, although it is not directly causal. It is likely that other factors contribute to the onset of periodontal disease, such as the disruption to the tooth row as the P4 erupts into a larger alveolar space left by the dp4.
- Correlations exist between alveolar recession and/or Type 2 PNB and tooth loss.
- The dental structures of sheep and cattle are similarly affected by oral pathologies.
- The result of inter-site comparisons indicates that external causal factors may be local, or population specific.

This study has also served to highlight some limiting factors to be considered in future archaeological studies of periodontal disease. Age has a considerable effect on the observation of oral pathologies, whether from the presence of Type 1 PNB on growing mandibles, or the increasing detection of alveolar recession, Type 2 PNB, calculus and tooth loss as animals get older. It is therefore vital that the age profile of any population is considered alongside the discussion of findings. Variation in results between populations from different sites is also important to realise and limits the scope of meta-analysis if factors such as environment, husbandry and physiological influences are not taken into consideration.

It is hoped that this study has provided a coherent summary of the nature of commonly observed oral pathologies, as well as practical requirements for the future interpretation of zooarchaeological data. It is imperative that the age of animals and the role of population-specific effects that include genetic, environmental and dietary factors are considered when explaining periodontal disease.

Funding

This work was supported by the European Research Council Feeding Anglo-Saxon England: The Bioarchaeology of an Agricultural Revolution. Under the European Union's Horizon 2020 research and innovation programme (ERC-2016-ADG-741751).

Acknowledgements

Thanks are extended to the ERC for funding the project, and the following individuals for access to site information and assemblages during the data-collection period: Leigh Allen, Southampton Museum; Naomi Bergmans, Oxford Museum Service; Lisa Brown, Wiltshire Museum; Rob Brown, Oxford Archaeology; Denise Buckley, Archaeological Project Services; Rebecca Craven, Lincolnshire Archives; Sheila Hamilton-Dyer; Neil Faulkner; Steve Ford, TVAS; Dawn Heywood, Lincolnshire Archives; Mark Hinman, Pre Construct Archaeology; David Ingham, Bedford Archaeology; Lorraine Mephram, Wessex Archaeology; Jacqui Mulville, Cardiff University; Rebecca Nicholson, Oxford Archaeology; Sian O'Neill, Pre Construct Archaeology; Alison Nicholls, The Potteries Museum and Art Gallery; Geoff Potter, Compass Archaeology; Dale Serjeantson; and Gabor Thomas, University of Reading.

References

- Aitchison, G., Spence, J., 1984. Dental disease in hill sheep: an abattoir survey. *J. Comp. Pathol.* 94 (2), 285–300.
- Al Sadi, H.I., Younis, H.B., 2010. Oral lesions in sheep in Mosul Area, Iraq. *Vet. Res.* 3 (2), 21–26.
- Albarela, U., 2019. A Review of Animal Bone Evidence from Central England. Portsmouth: Historic England 61-2019.
- Anderson, B., Bulgin, M., 1984. Starvation associated with dental disease in range ewes. *J. Am. Vet. Med. Assoc.* 184 (6), 737–738.
- Andrews, A., Noddle, B.A., 1975. Absence of premolar teeth from ruminant mandibles found at archaeological sites. *J. Archaeol. Sci.* 2 (2), 137–144.
- Ashwood, F., 2014. Lowland Calcareous Grassland: Creation and Management in Land Regeneration. The Land Regeneration and Urban Greenspace Research Group, Farnham.
- Atkinson, P., Spence, J., Aitchison, G., Sykes, A., 1982. Mandibular bone in ageing sheep. *J. Comp. Pathol.* 92 (1), 51–67.
- Baker, J., Brothwell, D., 1980. *Animal Diseases in Archaeology*. Academic Press, London.
- Banham, D., Faith, R., 2014. *Anglo-Saxon Farms and Farming*. Oxford University Press, Oxford.
- Bartosiewicz, L., 2008. Environmental stress in early domestic sheep. In: Miklíková, Z., Thomas, R. (Eds.), *Current Research in Animal Palaeopathology: Proceedings of the Second ICAZ Animal Palaeopathology Working Group Conference 1844*, 3–13.
- Bartosiewicz, L., Gál, E., 2013. *Shuffling Nags Lane Ducks: The Archaeology of Animal Disease*. Oxbow, Oxford.
- Britt, D.P., Baker, J.R., 1990. Causes of death and illness in the native sheep of North Ronaldsay, Orkney I. Adult sheep. *Br. Vet. J.* 146 (2), 129–142.
- Brown, W.B., Christofferson, P.V., Massler, M., Weiss, M.B., 1960. Postnatal tooth development in cattle. *Am. J. Vet. Res.* 21 (80), 7–34.
- Crabtree, P.J., 2018. *Early Medieval Britain: The Rebirth of Towns in the Post-Roman West*. Cambridge University Press, Cambridge.
- Crofts, A., Jefferson, R., 1999. *The Lowland Grassland Management Handbook*. English Nature, Peterborough.
- Davies, J., 2005. Oral pathology, nutritional deficiencies and mineral depletion in domesticates - a literature review. In: Davies, J., Fabis, M., Richards, M., Thomas, R. (Eds.), *Diet and Health in Past Animal Populations: Current Research and Future Directions*. Oxbow, Oxford, pp. 80–88.
- Davis, S., 2000. The effect of castration and age on the development of the shetland sheep skeleton and a metric comparison between bones. *J. Archaeol. Sci.* 27 (5), 373–390.
- DeBones, L.J., Mosier, D., Logan, E., Harvey, C.E., Lowry, S., Richardson, D.C., 1996. Association of periodontal disease and histologic lesions in multiple organs from 45 dogs. *J. Vet. Dent.* 13 (2), 57–60.
- Deniz, E., Payne, S., 1979. Eruption and wear in the mandibular dentition of Turkish angora goats in relation to ageing sheep/goat mandibles from archaeological sites. *Archaeozoology* 1, 153–163.
- Dobney, K., Brothwell, D., 1986. Dental calculus: its relevance to ancient diet and oral ecology. In: Cruwys, E., Foley, R. (Eds.), *Teeth and Anthropology*, 291. Oxford: British Archaeological Reports, International Series, pp. 55–81.
- Dobney, K., Jaques, D., Barrett, J.H., Johnstone, C., 2007. *Farmers, Monks and Aristocrats: The Environmental Archaeology of Anglo-Saxon Flixborough*. Excavations at Flixborough, Vol. 3. Oxbow, Oxford.
- Ducharme, N., Desrochers, A., Fubini, S., Pease, A., Mizer, L., Walker, W., Trent, A., Roy, J., Rousseau, M., Radcliffe, R., Steiner, A., 2016. Surgery of the bovine digestive system. In: Fubini, S., Ducharme, N. (Eds.), *Farm Animal Surgery*. Elsevier, Missouri, pp. 223–343.
- Dvorak, G., Reich, K., Tangl, S., Lill, C., Gottschalk-Baron, M., Watzek, G., Gruber, R., Haas, R., 2009. Periodontal histomorphometry and status of aged sheep subjected to ovariectomy, malnutrition and glucocorticoid application. *Arch. Oral Biol.* 54 (9), 857–863.
- Erjavec, V., Crossley, D., 2010. Initial observations of cheek tooth abnormalities in sheep in Slovenia. *Vet. Rec.* 167 (4), 134–137.
- Grant, A., 1982. The use of toothwear as a guide to the age of domestic ungulates. In: Wilson, B., Grigson, C., Payne, S. (Eds.), *Ageing and Sexing Animal Bones from Archaeological Sites*, 109. Oxford: British Archaeological Reports British Series, pp. 91–108.
- Greenfield, H.J., Arnold, E.R., 2008. Absolute age and tooth eruption and wear sequences in sheep and goat: determining age-at-death in zooarchaeology using a modern control sample. *J. Archaeol. Sci.* 35 (4), 836–849.
- Haimovici, A., Haimovici, S., 1971. Sur la présence de parodontopathies marginales sur des restes subfossiles de mammifères de stations pré- et protohistoriques du territoire de la Roumanie. *Bulletin de l'Groupe International des Recherches Stomatologiques* 14, 259–271.
- Halstead, P., 1985. A study of mandibular teeth from Romano-British contexts at Maxey. In: Pryor, F. (Ed.), *Archaeology and Environment in the Lower Welland Valley 1*, 27. East Anglian Archaeology, Ipswich, pp. 219–224.
- Hamerow, H., Bogaard, A., Charles, M., Ramsey, C.B., Thomas, R., Forster, E., Holmes, M., McKerracher, M., Neil, S., Stroud, E., 2019. *Feeding Anglo-Saxon England: the bioarchaeology of an agricultural revolution*. *Antiquity* 93 (368), 1–4.
- Hamerow, H., Bogaard, A., Charles, M., Forster, E., Holmes, M., McKerracher, M., Neil, S., Ramsey, C.B., Stroud, E., Thomas, R., 2020. An integrated bioarchaeological approach to the medieval 'agricultural revolution': a case study from Stafford, England, c. AD 800–1200. *Eur. J. Archaeol.* 23 (4) <https://doi.org/10.1017/aea.2020.6>: 1–25.
- Hammer, Ø, Harper, D., Ryan, P., 2001. PAST: paleontological statistics software package for education and data analysis. *Palaeontol. Electron.* 4 (1), 9.
- Hillson, S., 1979. Diet and dental disease. *World Archaeol.* 11 (2), 147–162.
- Hillson, S., 2005. *Teeth*. Cambridge University Press, Cambridge.
- Hirschfeld, J., Kawai, T., 2015. Oral inflammation and bacteremia: implications for chronic and acute systemic diseases involving major organs. *Cardiovasc. Haematol. Disord.-Drug Targets* 15 (1), 70–84.
- Hitchin, A., 1948. Relationship of occlusion and paradental disease in sheep. *Dent. Rec.* 58, 251–254.
- Holmes, M., 2011. *Food, Status and Complexity in Saxon and Scandinavian England: An Archaeozoological Approach*. Unpublished PhD Thesis. University of Leicester School of Archaeology and Ancient History.
- Holmes, M., 2014. *Animals in Saxon and Scandinavian England: Backbones of Economy and Society*. Sidestone, Leiden.
- Jones, G., 2006. Tooth eruption and wear observed in live sheep from Butser Hill, the Cotswold Farm Park and five farms in the Pentland Hills, UK. In: In Ruscillo, D. (Ed.), *Recent Advances in Ageing and Sexing Animal Bones*. Oxbow, Oxford, pp. 155–178.
- Jones, G., Sadler, P., 2012. Age at death in cattle: methods, older cattle and known-age reference material. *Environ. Archaeol.* 17, 11–28.
- Legge, A.J., 1992. *Excavations at Grimes Graves Norfolk 1972-1976: Animals, Environment and the Bronze Age Economy*. British Museum Press, London.
- Levitani, B., 1977. *Pathological Anomalies in Sheep Mandibles: a Methodological Approach*. Unpublished BSc. Thesis. University of London Institute of Archaeology.
- Levitani, B., 1985. A methodology for recording the pathology and other anomalies of ungulate mandibles from archaeological sites. In: Feiller, N., Gilbertson, D., Nga, R. (Eds.), *Palaeobiological Investigations*, 266. Oxford: British Archaeological Reports International Series, pp. 41–54.
- Li, X., Kolltveit, K.M., Tronstad, L., Olsen, I., 2000. Systemic diseases caused by oral infection. *Clin. Microbiol. Rev.* 13 (4), 547–558.
- Miles, A.E.W., Grigson, C., 1990. *Colyer's Variations and Diseases of the Teeth of Animals*. Cambridge University Press, Cambridge.
- Modeer, T., Wondimu, B., 2000. Periodontal diseases in children and adolescents. *Dent. Clin. North Am.* 44 (3), 633–658.
- Murphy, E.M., 2005. Animal palaeopathology in prehistoric and historic Ireland: a review of the evidence. In: Davies, J., Fabis, M., Richards, M., Thomas, R. (Eds.), *Diet and Health in Past Animal Populations: Current Research and Future Directions*. Oxbow, Oxford, pp. 8–23.
- O'Connor, T., 1982. *Animal Bones from Flaxengate, Lincoln c.870-1500, XVIII*. Lincoln: Lincoln Archaeological Trust: The Archaeology of Lincoln, 1.
- Page, R.C., Schroeder, H.E., 1982. *Periodontitis in Man and Other Animals*. Karger, Basel.
- Payne, S., 1973. Kill-off patterns in sheep and goats: The mandibles from Aşvan Kale. *Anatol. Stud.* XXIII, 281–303.
- Rodwell, J., 1992. *Grasslands and Montane Communities, British Plant Communities*. Cambridge University Press, Cambridge, p. 3.
- Silva, N.S., Silveira, J.A., Lima, D.H.S., Bonjardim, H.A., Brito, M.F., Borsanelli, A.C., Dutra, I.S., Barbosa, J.D., 2016. Epidemiological, clinical and pathological aspects of an outbreak of periodontitis in sheep. *Pesquisa Veterinária Brasileira* 36 (11), 1075–1080.
- Spence, J., Aitchison, G., Sykes, A., Atkinson, P.J., 1980. Broken mouth (premature incisor loss) in sheep: the pathogenesis of periodontal disease. *J. Comp. Pathol.* 90 (2), 275–292.
- Thomas, R., Johannsen, N., 2011. Articular lesions in cattle phalanges and their archaeological relevance. *Int. J. Paleopathol.* 1, 43–54.
- Thurley, D., 1987. Gingivitis around the deciduous teeth of sheep. *J. Comp. Pathol.* 97 (4), 375–383.

- Uzal, F., Plattner, B., Hostetter, J., 2016. Alimentary system. In: Maxie, M. (Ed.), Jubb, Kennedy and Palmer's Pathology of Domestic Animals. Elsevier, St Louis MO, 2 2-257.
- Wilson, B., Hamilton, J., Bramwell, D., Armitage, P., 1978. The animal bones. In: Parrington, M. (Ed.), The Excavation of an Iron Age Settlement, Bronze Age Ring Ditches and Roman Features at Ashville Trading Estate, Abingdon (Oxfordshire) 1974-1976, 28. Council for British Archaeology, Oxford, pp. 110–137.
- Zeder, M.A., Pilaar, S., 2010. Assessing the reliability of criteria used to identify mandibles and mandibular teeth in sheep, *Ovis* and goats, *Capra*. J. Archaeol. Sci. 37, 225–242.